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Biological Function as Influenced by Low Power Modulated RF Energy

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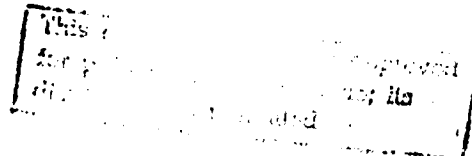
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### Abstract

In recent years, it has been recognized that low power density modulated rf energy can affect the functioning of higher living organisms. In this paper the sparse data generated in the western hemisphere on this subject is considered, the reasons for its sparseness noted, and the hypotheses on mechanisms that may provide an explanation for the observed effects and other possible effects are sketched. Possible conclusions with regard to hazards to personnel are then considered.

In recent years, there has arisen in the United States a recognition that low powered density, modulated rf energy can affect the functioning of higher living organisms, i.e. mammals. This recognition is based upon the relatively small volume of data generated by investigators in the western hemisphere and the rather large body of data generated by investigators in the Soviet Union, Czechoslovakia, Hungary, and Poland.

In an analytical review published six years ago, this writer critically considered the data available up to that time regarding the effect of rf energy on the functioning of living organisms, particularly neural and behavioral function (Frey, 1965). In this paper, the writer will not update his prior paper by reviewing the rather large and increasing volume of data that has been generated in the East European countries since then. There are several recent reviews of that data available (Dodge, 1969; Library of Congress, 1966) and it will be reviewed again elsewhere in this issue of the journal.

This paper is instead intended to be a selective review of the data that has bearing on the effects that can be expected to occur in higher organisms with low level rf energy illumination. To avoid duplication within this issue, the East European data is excluded from this review, except for occasional necessary reference. The same restriction applies to the data reported in the Tri-Services Conferences i.e. most of the data gathered in this country prior to 1961. It can be noted that the Tri-Services Program data, though much of it is quite good, is largely irrelevant to the topic of this paper.

What shall be included is the sparse data on higher organisms that has been gathered here since the Tri-Services Program ended. Much of it will be the writer's, since he is the only one of the new generation of

Investigators, (those primarily interested in low level effects) who has been active long enough to have published more than one or two papers in the area. This data review will be introduced with an answer to the obvious questions of why the Tri-Service program data is largely irrelevant to this paper and why the data generated in this country since then is so sparse. Then to complement the sparse data, data from other areas that directly bear on the possible mechanisms for low level effects will be discussed, particularly those involving the nervous system because so much of the East European data indicates that it is the system most sensitive to rf energy. This discussion of the possible mechanisms is intended to provide the hypotheses needed to interpret present data on low level effects and to indicate under what conditions and in what manner they will appear. I will then conclude with a brief discussion on what conclusions can be drawn from presently available data on the possible hazards of low level rf energy.

#### Reasons for the Sparseness of Data

First, let us take up the matter of the lack of relevance of most of the Tri-Service program data to the topic of this paper and for the sparseness of the later data gathered in the United States.

There were a number of factors that operated and contributed to this state of affairs. The first factor resulted from the assumption, when the Tri-Service program was organized, that the only possible effect was the "heating" of tissue. Some people involved in that program quite confidently showed by means of equations that neural function could not be affected by rf energy. About the time of the last Tri-Service conference, when I first became interested in this area, I can recall being shown on a chalk board the calculations that "proved" that nerves cannot be affected by rf energy. The line of reasoning is defective as will be shown later when

mechanisms are discussed.

Thus, through the acceptance of a false assumption, the only nervous system investigation initiated in the Tri-Service program consisted of a small study in which the investigators were given an X band transmitter as an rf source. Since one cannot penetrate the skin to a significant extent with X band energy, the best that could be done were marginal studies on stimulation of peripheral nerve endings.

The second factor contributing to the sparseness of the data can be traced to the controversy that developed during the Tri-Service program on the thermal vs non-thermal effects. A very heated controversy developed between those who thought that only thermal effects could occur and those who thought non-thermal effects could also occur. In general, the investigators were talking past each other because there never was a common definition of the words thermal and non-thermal.

A third factor was the tendency of the above mentioned investigators to reject East European data for various good and bad reasons.

One reason was due to the differences in tradition in U.S. and U.S.S.R. biology. American investigators are oriented to looking for effects through a microscope. Investigators in the Soviet Union have a somewhat different tradition. They tend to look for effects in the modification of behavior as reflecting nervous system function. Since there was no one in the behavioral area substantially involved in the American program, there was no one who had the background to evaluate and interpret the significance of the Russian work. Instead,

it tended to be dismissed as alien and uninterpretable.

Another factor involved in the rejection of the Russian work was the fact that many of the translations of the Russian work were inadequate and even misleading. One can easily understand the negative view of American investigators who evaluated the work through these translations. Note should be taken though that some of the Russian work was of poor quality.

An additional reason for the negative view of American investigators was the fact that the Russians often did not give information in their papers which we feel is necessary to evaluate the quality of the research. Russians working in some other areas also do not give sufficient information to evaluate and replicate their work.

Whatever the reason, the possibility of replicating experiments is very much in question. It would seem that an investigator would have to do as Morrell (1963) did to insure the validity of his replication. Morrell "replicated" an experiment reported from the U.S.S.R. involving the application of low current densities to the brain to induce behavioral effects and obtained negative results. Shortly thereafter, he visited the U.S.S.R. and received all the details on the experiment and upon his return was able to in fact replicate the experiment and confirm the Russian work.

There were other factors, non-technical factors that influenced and limited the direction of research.

#### Consideration of the Sparse Data

The writer will now consider this sparse data. The review will

be largely confined to the UHF band since most of the significant data on low level effects has been obtained using sources in this band. In general, known low level effects are minimal outside of this band. A reason for this can be found in Fig. 1. Energy at frequencies within this band tends to penetrate and be deposited

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Insert Fig.1 about here

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within the body. Related to this is the recent observation (Heath, personal communication, 1970) that there is a narrow group of frequencies within the UHF band, between the frequencies of 0.910 and 0.930 GHz, which are particularly stopped by the human head. The review will also be largely confined to data obtained using average power densities of less than 20 mw/cm<sup>2</sup>.

Now that I have defined what rf effects data will be reviewed and the reasons for the selection, I will consider the data itself. Since most of it has been published and an exhaustive review of it would be lengthy because of the experimental controls involved, I shall summarize the various studies and provide the references

After initial exploratory work (Frey, 1961, 1962, 1963, 1963a) and a comprehensive review of the area (Frey, 1965), I initiated a program to explore the experimental controls necessary and to develop the techniques and equipment necessary for the study of biological

function under low power rf energy (Frey, 1966, 1967, 1968, 1968a, 1968b). This work was then extended into the study of the nature of the phenomenon (Frey, 1970, 1970a). The results of this series of experiments can be considered to center about four major themes, i.e., experimental controls and techniques, brain function, sensory function, and heart function. Although results of the work on experimental controls and techniques are too extensive to review in detail here, it is emphasized that these are critical for accurate data collection. As a sampling, comparative studies of biological data recording techniques such as the use of various recording electrode systems in the rf field have been studied. It was found that certain conventionally used systems yield artifacts as data due to induced currents stimulating the tissue as well as feeding into the recording pre-amplifier. It was found that filtering has limited usefulness and that lead placement is of consequence. New types of recording electrodes were developed which show excellent characteristics in the rf field (Frey, Frazer, Siefert, and Brish, 1968; Frey, 1967). Experiments were also carried out to develop IR techniques to remotely monitor the activity of nerves in an rf field. In this way neural activity could be monitored with no recording devices in the field (Frazer and Frey, 1968). This latter study also had another objective of wider significance which also has bearing on rf effects (Magineanu and Moisescu, 1970).

Studies were also made of restraint devices to hold animals and of the field distorting effects of these devices. Polystyrene



head holders were developed for use with cats, teflon and nylon chairs and restraints were developed in studies with monkeys, and wooden enclosures and restraints were developed for use with cats (Frey, 1967; Frey and Thornton, 1966). Studies were also carried out using three dimensional field plots to investigate the effect of the biological object itself on the field within an echosorb enclosure. Similar studies were made on the effect of the field measurement device on the field. Standardized methods of measurement and reporting of measurements were developed. Experimentation was also carried out to determine the effect of body position and orientation on results. Studies were made of shielding materials and their usefulness in experimentation in determining critical areas of the body in illumination with rf energy (Frey, 1967).

It was found that carrier frequency, and the relationship of the modulation to the function in its phases are critical in the effect of low power density rf energy on some functions of higher organisms (Frey, 1962, 1963, 1967; Frey and Siefert, 1968). For example, perception in the auditory system can be induced with carrier frequencies that penetrate the head but not those that do not penetrate the head, e.g. at 1 GHz but not at 10 GHz. The auditory system perception cannot be produced unless the carrier is modulated. The brain stem responses have not been observed with an unmodulated carrier. The isolated frog heart cannot be driven to arrhythmia if the rf pulse impinges upon the heart at the P wave but it can be so driven if the rf pulse impinges at the occurrence of the R wave.

It was found that there are critical body areas (Frey, 1967). Peak rather than average power density was determined to be the more important variable in the study of the effect of modulated low power density rf energy on biological functions (Frey, 1962, 1967).

As may be seen from this sampling, there are many factors to be controlled and special techniques must be used in biological work with rf energy. The writer considers these investigations of experimental controls to be the most significant and useful portion of his work.

As may be seen in the literature though, until quite recently many of these control factors have not been reported upon in published studies and may or may not have been incorporated in the studies (Frey, 1965).

Turning now to data specific to brain function, I shall summarize the information obtained by illuminating cats with pulse modulated UHF energy and observing for evoked activity in the brain (Frey, 1967). The threshold power density necessary to evoke activity was approximately 30 microwatts/cm<sup>2</sup> average, and 60 milliwatts/cm<sup>2</sup> peak. The controls indicate that the activity was neural evoked activity rather than an artifact of the situation. Using an echosorb shield to cover the entire cat, or head, or body, it was found that the head must be exposed to the UHF energy in order to have an effect occur. Within the carrier frequency range used (1.2 - 1.525 GHz), there appeared to be a reduction of effect at the highest frequency. Variation in power density has a distinct effect on the evoked activity. Polarization of the energy, whether perpendicular or parallel to the spine, did not seem to have much effect though this is not unequivocal. As pulse-repetition-frequency (PRF) was changed, the evoked activity did not change significantly until the PRF was greater than approximately 50 pulses/sec. When greater than this, there was often an overlap in activity evoked by the series of stimuli. In general, recording from the rostral brain stem did not yield evoked activity as diffuse and

persistent as recording from the caudal portion of the reticular formation of the brain. This is as one would expect from these two brain areas and is a further indication that the data are not artifacts. In Fig.2 and 3, typical brain tracings are shown.

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Insert Fig.2 & 3 about here

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Sensory effects have also been studied in this laboratory (Frey,1963). "Tactile" stimulation in humans at carrier frequencies in the VLF range (Frey, 1963) and auditory effects in humans and apparently in animals at UHF have been found (Frey, 1961, 1962). Radiated UHF energy can be perceived by humans as an auditory sensation. The thresholds are shown in Fig.4. The effect was induced with average power densities of  $100 \mu\text{W}/\text{cm}^2$ .

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Insert Fig.4 about here

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The important parameters were peak power density, carrier frequency, and modulation. The experimental arrangement ruled out factors such as rectification by fillings in the teeth. The most sensitive area was the region over the temporal lobe of the brain. Meahl (personal communication) and others have also noted an auditory effect with rf sources possessing the characteristics specified by the writer.

Initially this writer felt that the rf effect and the electrophonic

effect might be comparable, and a technique had been found that could be used to explain the electrophonic effect (stimulation of sensation in the auditory system with electric current). Flottorp (1953) was the most recent investigator of the electrophonic effect. Flottorp suggested five possible mechanisms by which impressed current could cause the electrophonic effect. The writer undertook experimental studies and a mathematical analysis considering the possibility of rf radiation pressure vibrating the skin and thus accounting for both effects. The analysis indicated that the rf auditory effect and electrophonic effect are not the same phenomenon.

Interestingly, as an incidental extension of a limited electrophonic effect study, Sommer & Von Gierke (1964) tried a calculation to test the same possibility. They selected portions of the writer's published data and tentatively concluded that rf energy induced an auditory sensation by vibrating tissue such as the skin. Unfortunately, they apparently were not familiar with the rf literature. They made untenable assumptions for use in their calculations, they used an incomplete equation, and apparently missed seeing data that the writer published that showed that at certain carrier frequencies there was no auditory effect. These carrier frequencies happen to be frequencies that Sommer & Von Gierke's analysis would indicate to be the best frequencies to induce the auditory effect.

Before rejecting his initial hypothesis, the writer searched for cochlear microphonics in guinea pigs and also in cats exposed to rf energy. No cochlear microphonics were found in either species. Control tests with acoustic energy of comparable waveform and loudness, including the alternation of acoustic and rf energy, indicated that a microphonic does not occur with rf energy. The power densities used were far above that needed to induce the auditory effect in cats. This would suggest that the sensor may not be prior

to the inner ear.

The investigation was carried further by first conditioning cats to respond to rf energy cues and similar acoustic cues. Then the cochleas were destroyed surgically in some cats and with neomycin in other cats. Unfortunately, the results of this study are not complete. The use of that particular transmitter was lost just as the final stage of the experiment was reached. Thus, no conclusions can be drawn.

Concurrently with the foregoing work, another line was pursued to obtain suggestions as to the locus of the rf hearing sensing mechanism. Using energy threshold levels obtained at two different frequencies for the hearing effect in humans, the rf energy was mathematically traced through a mathematical model for forehead tissue. The in air threshold measures were unequal at the two different carrier frequencies. An attempt was made to determine mathematically when the rf energy became equal through losses in passing through tissue. Such an equality point, the crossing of signal strengths, would suggest where to look for the sensing mechanism. In constructing the model, all tissue electrical values were selected in advance, standard values for tissue thickness used, and first reflections were taken into consideration. The calculations indicate that the first rf energy crossing is in the cortex of the brain as is shown in Fig. 5. It is

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Insert Fig.5 about here

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emphasized that this should not be construed as a proof of sensor location.

Experimentation was also carried out with cats to determine if avoidance conditioning could be established. Cats can use the rf energy as a cue in avoidance conditioning and rf energy thresholds have been established. Indications of avoidance behavior in monkeys have also appeared in experiments, though at relatively high power densities.

The last major theme of this writer's experimentation to be reviewed is heart function. I have pursued a line of experimentation independent of the Russian work due to the impossibility of replicating their work with the information available on their technique (Frey, 1963). I studied the function of the isolated frog heart stripped of its natural neural and hormonal buffer systems (Frey & Siefert, 1968). Using pulsed modulated rf energy at 1.425 GHz that was synchronized with selected portions of the heart cycle we found that the heart was responsive to rf energy.

When the heart was illuminated 200 msec after the P wave, about the time the QRS complex occurred in the experimental situation, the beat-rate increased. This increase was statistically significant at the .01 level. No clear effect was shown when the heart was illuminated at earlier points in the cycle. In half the cases, arrhythmias occurred and they were associated with rf illumination. On occasion, the heart ceased after a period of arrhythmia.

The results of control sessions in which the possibility was tested that induced currents on the electrodes caused the effect, indicate that the effect can not be attributed to induced currents. This possibility was explored even to the point of using, at the same time, voltages  $10^2$  higher and  $10^3$  longer than the maximum that the UHF energy induced on the electrodes.

The results of the control sessions for determining if illumination with rf energy is necessary to induce the effect, indicate that illumination

is necessary. When echosorb shielding was interposed between the antenna and preparation, no effect appeared.

Leaving the summary of the writer's work, we summarize below some of the work of others of the new generation of Investigators. This section will necessarily be brief since, in general, they have as yet completed only one or two studies.

Hern (1965) has explored the effect of long continued low intensity rf energy on visual acuity and the frequency at which a flickering light appears to become steady. Forty albino rats were used as subjects (Ss). The experiment consisted of two phases. Experimental Ss were exposed to low intensity low frequency (300 to 920 MHz energy) for 30 to 45 days in phase 1 and phase 2 of the experiment, respectively. Horizontal and vertical bar patterns were used as stimuli in phase 1 and the stimuli in phase 2 consisted of a flickering light and a stationary light.

Daily visual pattern and flicker threshold measures were obtained for 30 and 15 consecutive days in phase 1 and phase 2, respectively. The possibility of rf radiation affecting the motivation level of the experimental subjects was also investigated in a separate study. Twenty subject were randomly assigned to experimental and control groups with ten Ss irradiated and ten Ss non-irradiated. The study was conducted over a 30 day period and food consumption was used as an indicator of motivation.

His analysis revealed significant differences in the flicker thresholds of the irradiated as compared to the non-irradiated subjects. The magnitude of these differences increased with time. It should be noted that flicker threshold is a sensitive well established indicator of brain function.

No significant differences were found between irradiated and non-irradiated subject in visual pattern thresholds. Since no differences were

found in food consumption it would seem that motivation is not a confounding variable in these experiments.

Korbel & Thompson (1965) exposed 10 albino rats to low intensity rf energy (300 - 920 MHz presented in ascending and descending sweeps) for 47 consecutive days. They found that irradiated subjects were more active than non-irradiated subjects for a short period of time during the early part of the experiment, but they became less active than the non-irradiated Ss as the days of radiation exposure increased. The lowered activity level extended from day 30 until activity measures were ended on day 40. The irradiated group also showed increased emotionality.

In a follow up study, Korbel & Fine (1967) explored for a possible relationship between rf frequency range and activity level. In experiment 1, a lower frequency range (320 - 450 MHz) was used, while a higher frequency range (700 - 900 MHz) was used in experiment 2. Identical low power levels were reported to have been maintained for both experiments. Exposure to each frequency range was reported to decrease activity as compared to controls with the lower range more effective.

Bourgeois (1967) explored the effects of exposure to rf radiation on the auditory thresholds of humans. Thirty-six male volunteers between 18 and 25 years of age and possessing normal hearing were exposed to low intensity radiation at 1 GHz for 2 minutes previous to and during the presentation of the auditory stimuli. He used three modulation conditions i.e. 400 Hz, 1,000 Hz, and no modulation. The thresholds for 500 Hz, 2000 Hz, and 5000 Hz acoustic energy were determined. Analyses revealed that exposure to rf radiation resulted in a significant decrease in the auditory thresholds. The threshold change was found to be a function of the type of rf energy modulation used since the auditory thresholds were significantly



lower upon exposure to the 1000 Hz modulated rf radiation than upon exposure to 400 Hz modulated rf radiation.

Dardano (1969) has initiated experimentation in which he is looking into the turnover rate of serotonin and norepinephrine in the rat brain. These hormones are indicators of brain function. As yet, his work is still in the exploratory stage and no conclusions can be reported.

Justesen & King (1969) have embarked upon a rather different line of investigation. They decided to set up a highly specific model situation and to study all variables within it. They are carrying out their experimentation within an oven enclosure at 2.45 GHz with a complex modulation pattern. They are using three average power levels that are reported to be in the vicinity of 10 mw/cm<sup>2</sup>. Their data are reported to suggest a curvilinear relationship between rate of responding in a learned task and rf power level. At their higher rf levels, they found depression of activity and, at the extreme, reversible flaccid paralysis. Due to the depression of S activity, they could obtain only limited information on rf energy as a cue or its effect on the discrimination of cues. Note should be taken that one can not generalize their results to the free field situation. They have set up, as they intended, a highly specific model situation.

As may be seen in this summary of the reports from the new generation of Investigators, there is a large set of questions to be answered, questions that were neither recognized nor addressed during the Tri-Service Program for the various reasons mentioned in the early portion of this paper.

#### Possible Mechanisms

The next logical question, what could be the mechanism for these and other possible low power density effects, will now be considered. A number of suggestions have been made as to a mechanism whereby low

power density rf energy can effect living organisms. In this section, I sketch a selection of possible mechanisms that I judge at this time, to have most relevance to higher organisms such as man. In particular, the possible mechanisms that have bearing on nervous system function will be discussed.

First, two views that were first offered in the late 1950's will be discussed.

Although offered as generalizations, each view can be shown to have very limited applicability. The discussion will then be expanded to include a number of alternate possibilities, only a few of which have been previously offered within the context of a discussion of rf effects. In this way, the theoretical bases for the expectation of low level effects of rf energy will be laid.

The first view to be discussed will be McAfee's. He addressed himself to a question that arose early in the Tri-Service Program. It had been observed that anesthetized animals could be aroused with rf energy. There was a good bit of controversy over the mechanism by which this occurred. McAfee (1962) carried out an interesting set of experiments in which he established that with a fairly high power density i.e.  $200 \text{ mw/cm}^2$ , at a carrier frequency at which most of the energy is deposited in the skin i.e.  $\sim 10 \text{ GHz}$ , that one could heat the skin and stimulate the skin pain sensors. Thus, a justified and probable interpretation of the arousal of animals from anesthesia by high power rf energy at frequencies which do not penetrate the body is that there is stimulation of the skin pain receptors. Unfortunately, however, he has taken the position (McAfee, 1969) that rf stimulation of the nervous system can only be through stimulating the skin pain sensors. This is clearly untenable. His own data indicates that

such a mechanism does not provide an explanation for effects found at carrier frequencies at which the skin is largely transparent to rf energy. Further, his own data shows that such skin sensor effects are not to be expected at low power densities.

The second untenable view that can be traced back to the 1950's is that of Schwan. He stated that it is not possible to stimulate the nervous system with rf energy (Schwan, 1969). He bases this conclusion on calculations he made on a mathematical model of the neural membrane. His calculations indicated that at field strengths that are "not thermally significant", the induced potentials across the nerve membrane are many orders of magnitude smaller than the nerve resting potential. He states that such induced fields applied to the resting potential of nerves cannot excite the nerves.

There are two defects in his line of reasoning. One defect is the assumption that we have a good understanding of nervous system function. This assumption is wrong. Our understanding of how information is coded, transferred, and stored in the nervous system is virtually nil. We have, at best, multiple hypotheses concerning this, none of which has much support nor is any generally accepted as truth. Thus, a conclusion such as Schwan's based upon calculations using assumptions about information coding, transfer, and storage in the nervous system is unacceptable. He must first prove the truth of his assumptions on information handling in the nervous system before his conclusions can be accepted.

The other flaw may result from his lack of familiarity with nervous system function. Even if we could accept the particular nerve model he has chosen, we find that his conclusion still collapses under scrutiny. He compares the rf induced field against the resting potential of the nerve. But nerves function. The resting potential is only one extreme of a continuum of neural states. A consideration of only the resting potential does not yield a model that corresponds to reality, at least, the reality of the nervous system of man, monkey, cat and frog.

As a matter of interest, let us consider his model, but functioning. The nervous system of man, monkey, cat and frog can be characterized as constantly being in a state of activity with the voltage across the neural membranes constantly fluctuating, collapsing, and even reversing. Using such a functioning model and accepting Schwan's statement that there are voltages induced across the membrane by an rf field "...introducing typical values of  $p_1$ ,  $p_m$ ,  $C_m$  at field strength values which are not thermally significant one obtains potentials  $\Delta v$  which are about  $10^5$  or  $10^6$  times smaller than the resting potential." (Schwan, 1969), let us consider the implications. This means that we can expect induced fields across the membrane on the order of 5 to 50 volts per cm. This is within the physiological range to induce excitatory and inhibitory effects in the nervous system. This is well documented and some of the evidence will be cited.

Aladzhalova and Koekina (1968) have shown that microamp range currents affect the firing of the action potential though not being stimulating in themselves. Further, the effect is dependent in part upon the functional

connection existing before the application of the electrical field. Terzuolo and Bullock (1956) reported that the action potential is affected by electrical fields of 8-12 millivolts per centimeter. Rusinov, and later, Morrell (1963) found that application of very low extracellular currents on the order of 10 microamps will sensitize an organism such that it will make a motor response for a wide variety of stimuli. In itself, however, the extracellular electrical current does not fire off action potentials. Rusinov and Ezrokhi (1967) looked rather deeply into the matter of ephaptic interaction of neurons through the electrical field generated by them. As a result of their studies, they concluded that significant physiological effects result from low level electrical fields. This includes synchronization effects produced by just the extracellular fields created by nearby neurons. They suggest that neurons of the central nervous system may have a substantial sensitivity to extracellular electrical fields in view of the modulating effects of E fields on the action potentials that they observed. Segal (1968) experimentally studied the possibility that fixed charges determine the electrical behavior of excitable membranes, such as the neural membrane. He believed that many macroscopic membrane phenomena can be explained as the simple and immediate consequence of the presence of high density immobile charge groups within the membrane. In his experimentation, he demonstrated that the shear surface of squid and lobster giant axons bear fixed electrical charges and that these can be related to the electrophysiological state of the axon. Thus, he has evidence that the axonal surface is not a passive structure but one whose intrinsic physico-chemical attributes can be affected by external electrical forces. One of the most interesting of his findings is that there was action potential conduction block when a transaxial electrical field was applied and maintained for a

period. As he points out "...the magnitude of the membrane current due to the fields employed should not be very great in terms of those that flow during the course of an action potential." He further points out, after making calculations involving an imposed electrical field and the action potential field, that the imposed electrical fields he used are small fractions of the peak current density occurring during an action potential.

Thus, when we consider a functioning nervous system, we find that Schwan's calculations lead to the conclusion that the nervous system can be affected by rf energy.

So much for the logic and hypotheses of McAfee and Schwan. It is not enough though to only provide the basis for dismissing hypotheses. It is now incumbent upon the writer to provide alternative hypotheses.

Providing alternate hypotheses is no problem. The problem is which of a number of reasonable hypotheses to consider and use. This problem is a result of our ignorance of how the nervous system codes, transfers and stores information.

Biology, particularly the biology of the nervous system, is today in a state of flux. Theories derived from Bernstein's hypothesis, first offered in the early 1900's, that the nervous system functions somewhat like a telegraph with the action potential or electrical spike recorded from nerves as the information carrier, have been found to be less than adequate. As a result, newer concepts have been developed, concepts based in large part on solid state physics. In these newer hypotheses, the action potential is not considered to be the primary information carrier as it is considered to be in the conventional biology based upon the telegraph model.

For convenience, the following discussion of possible mechanisms through which rf energy can affect the nervous system is organized into hypotheses involving the older concepts of nerve function and then hypotheses based upon the newer concepts of how nerves function. Two particularly relevant hypotheses based upon the older concepts of neural function are those of Valentinuzzi and MacGregor.

Valentinuzzi (1965) used a mathematical approach to explore the possibility that magnetic fields affect the nervous system. He centered his attention on the axon membrane and its electrical behavior and on the ectoplasm and its metabolic activity. An analysis involving magnetic field effects is not equivalent to one involving microwaves, but there are some aspects of his analysis which have relevance for hypothesis generation for the microwave area.

He used equations to evaluate the effects of magnetomotive force on ions, magnetic induction of electrical fields, and magnetic changes of inductance. The equations indicate that the affect of a static magnetic field upon an axon would be almost undetectable instrumentally. He does not stop, however, at that point. He recognizes that living organisms are composed of more than a single axon. Thus, he extended his equations to consider the nervous system functioning as a whole. The results of this extension lead him to suggest that a magnetic field may influence the activity of the nervous system through multiplication and addition of small biophysical effects. He points out that a great number of pathways typically converge at a synapse. He notes that Rashevsky (1960) has demonstrated that addition effects occur in them. Thus, he concluded that "...if several chain pathways which reach a nervous center convey excitation

already magnetically distorted by multiplication, the center may not fire because the addition of stimuli is below the center threshold." The writer would venture the suggestion that a consideration of Valentinuzzi's paper may well be helpful in the generation of hypotheses relevant to rf effects.

Turning now to a sophisticated consideration of the possibility of rf energy affecting the nervous system within the context of conventional biology, the writer will discuss the analyses and hypothesis of MacGregor. MacGregor's specialty is the modeling of neural networks (MacGregor, 1968). Thus he starts with a realistic model of a functioning nervous system. Using it, he mathematically explores the idea that the electrical component of microwave radiation might induce transmembrane potentials in nerve cells and thereby disturb neural function and behavior. He considers steady and modulated rf fields and estimates through a series of equations the transmembrane currents and potentials that can be expected. He concludes that the intracranial electrical fields associated with low intensity microwave illumination "...may induce transmembrane potentials of tenths of millivolts (or more) and that, therefore, such externally applied fields may disturb normal nervous function through this mechanism." He notes that an E field of two volts per centimeter at megahertz frequencies could produce a neural transmembrane potential of tenths of a millivolt. His analyses indicate that the induced transmembrane potential should exhibit a maximum at frequencies in the UHF band. Further, he finds that large cell components in regions of high cell density should be most influenced by extracellularly applied fields.

The coincidence of MacGregor's analyses with experimental results is interesting. For example, Frey (1962) reports that the threshold for the rf hearing effect is a peak E field of 14 volts per centimeter at megahertz



frequencies. MacGregor's paper might usefully be read.

I shall turn now to some of the newer concepts of neural functioning, concepts that are more in line with the writer's thinking.

Harmon and Schmidt-Nielsen provide what we can use as a succinct introduction. "The heart of the problem in obtaining meaningful knowledge of nervous systems is in understanding neural coding and decoding. Yet, paradoxically, our comprehension of the language of nervous action is almost nonexistent." (Harmon, personal communication). Schmidt-Nielsen (1964) also recognized the questionable validity of the action potential as the information carrier in the nervous system. "The easiest way to discover that an impulse passes a nerve is to measure the electrical changes in the nerve fiber... the change in potential developed during the brief period of activity is called the action potential. But we must point out that the action potential is not the nerve impulse itself. It is only a means of showing that something does happen."

The point in presenting these quotations is that we should recognize quite clearly that implicit in the conventional view of neural activity is the assumption that the measured electrical signals reflect the operations involved in information processing. In the following concepts of nervous system function, this questionable assumption is largely rejected. In these concepts, we shall see many possibilities for rf effects mechanisms.

We shall consider first Szent-Gyorgyi's thinking. Szent-Gyorgyi (1968) points out that though in several instances donor-acceptor interactions in biological substances had been produced in vitro, the idea of charge transfer found no real place in biology for many years. It was thought that strong charge transfer could play no role in biology. It was believed that strong oxidizing agents are incompatible with life and that

there is no light in the body to move electrons. Szent-Gyorgyi however showed, using ESR techniques, that even molecules with low reactivity, with a major role as metabolites or hormones, can give off an electron and form a free radical. This suggested to him that charge transfer may be one of the most common and fundamental biological reactions. On the basis of his experimental results, he proposed a quantum mechanical view of biology (Szent-Gyorgyi, 1969). In his view, the solid matter and the water of a cell constitute a unified structure. Further, he proposed that cellular processes be understood in terms of the transport of electrons and energy within the structure. In essence, in his view the cell is a solid state system and, as in a crystal or metal lattice, the possible energy levels within the cellular water lattice that can be occupied by individual valence electrons are viewed as fusing into common energy bands. Thus, as in ordinary crystals, electrons belong not to one or two atoms alone but to the whole structure. Large organic molecules may also be viewed as entities with common energy levels existing as in protein. In recent years, evidence for this view has been mounting. We see that the cell can no longer be viewed as a container filled with ions and macromolecules in a liquid water solution. Cope (1969) using nuclear magnetic resonance spectroscopy found that the water in brain tissue is bound in a highly ordered structure that can best be described as crystalline. Fritz and Swift (1967) studied the high resolution proton magnetic resonance spectrum of the sciatic nerve of the frog in both the state of firing and in the resting state. They found that the proton spin-spin relaxation time of the proton intracellular water decreases significantly when the cell fires. Based upon the signals that they observed and the controls incorporated in the studies, they concluded that marked changes occur in the state of the intracellular water when nerves depolarize.

Thus, we have a foundation, a biological substrate, upon which rf effects can play.

A variant of Szent-Gyorgyi's view, a view specific to the nervous system has been detailed by Wei. Wei (1966) suggests that the neuron has the structure and potential profile of a PNP transistor. He points up that in a transistor, the emitter barrier is lowered by applying a forward bias which draws carriers away from the junction. In an axon, he suggests the outer barrier is lowered by applying a cathodic potential which causes dipole flipping. Since the physical principles governing the dynamics of charged particles are the same, he sees no reason why the axon would not take a transistor action once its outer barrier is lowered. Such a model does encompass many features of nerve conduction. In part, Wei uses as evidence for the accuracy of his model the discovery by Segal, (1968) of negative fixed surface charge on membranes, the birefringence change observed by Cohen, Kuines, and Hille (1968), and the report of micron wavelength emission from nerve by Frazier and Frey (1968). He has also suggested (Wei, 1968) that what have been assumed to be transmitter chemicals in the central nervous system, e.g. acetylcholine, are actually electrical dipoles which when oriented and arranged in a large array could produce an electric field strong enough to drive positive ions over the junction barrier of the postsynaptic membrane. In this way, they would initiate excitation or produce depolarization. This hypothesis of his can explain a great number of biological facts such as the cleft size at synapses, synaptic delay, non-regeneration, subthreshold integrations, facilitation with repetition, and the effects of calcium and magnesium. It also provides a basis for explaining why acetylcholine acts as an excitatory or inhibitory transmitter under different circumstances. Thus, he has

incorporated within an electrical framework synaptic transmission, a phenomena that appeared to involve chemical mediation. He has recently extended his theorizing (Wei, 1969) and now accounts for an even wider range of neural phenomena. With Wei's theory, we have a well worked out conceptual framework within which we can pose questions on the possible effects of rf energy on neural function.

There is another line of evidence related to Wei's hypotheses. Becker (1965) has carried out an extensive series of experiments exploring what he considers to be a neural semiconduction control system in various living organisms. He reports he observed Hall voltages which are directly related to the physiological state of nerves. On the basis of the data he has gathered, he suggests as a conceptual framework the movement of mobile charge carriers within a solid state neural system.

New concepts on the nature of neural function have also come from Batteau (1963) as a result of his study of the mechanism of hearing. He suggested that sensation in the organism is due to the shifting of the probability of transition of electrons from the excited state to the ground state in organic molecules. He believed that the action potentials that are typically assumed to be the information carriers are metabolic artifacts and not carriers of sensory signals. To test this view, he initiated a series of experiments on moth and frog nerves and muscles. These experiments yielded data that tend to support these concepts. In experiments on the electrical spike frequency variation with temperature in the B cell of the Catocala moth ear, he obtained data that he interpreted to indicate a transition energy gap of about 0.35 electron volts, corresponding to a 3 micron wavelength signal. In subsequent tests with the frog sciatic nerve gastrocnemius muscle preparation, he found that spontaneous muscle activity would

occur prior to the electrical spike activity of the nerve and muscle. On the other hand, when the preparation was stimulated in the typical fashion with electrical shocks, he observed the typically observed phenomena of the electrical spike on the nerve prior to the mechanical activity.

Augenstein (personal communication) in viewing the nervous system as a solid state system has addressed himself primarily to information storage. He has considered macromolecular conformation changes as possible information storage mechanisms in nerves. He reports that conformational changes take place in neural membranes and suggests that proteins have the properties required of flip-flops. He suggests that, as such, they are involved in neural information processing and storage.

In his experimentation, he used UV energy to explore the flip-flop characteristics of proteins. After establishing that they do have such characteristics, he extended his experimentation. On the basis of this extended experimentation, he suggests that changes in protein comparable to those produced by UV can be produced by electrical fields of the order of magnitude of those which exist in the brain. He reports that with current flows in potential fields comparable to those which exist in the brain, it is possible to modify trypsin sufficiently to destroy its enzymic activity. He further suggests, reasoning from data that indicates that a few hundred volts per cm can produce electroluminescence in anthracene, that electrical fields applied to the brain at this level may well cause excitation to at least low lying excited levels. He concludes that there are neural conformational changes which are significant in information transfer and storage in the nervous system. His data shows that electrical fields at levels that can be expected from rf energy at low power densities could influence these conformational changes.

Supporting Augenstein's views, are the findings of several other investigators. Neural function is considered by several investigators to involve reversible cooperative change in conformation of macromolecules in the nerve membrane (Tasaki, 1968; Changeur, et al, 1967; Lehninger, 1968). Experimental studies using the optical properties of nerves as the datum support the view that a conformational change associated with function does take place in the neural membrane. These include reports by Cohen and Keynes (1968), Tasaki, Watanabe, Sandlin, and Carnay, (1968), and Tasaki, Carnay, Sandlin, and Watanabe (1969). In the later paper, for example, the writers studied the fluorescence of crab and squid nerves that were dyed with acridine orange. They found that the intensity of fluorescence increases during nerve function. Since the fluorescence of this dye is strongly influenced by changes in the microenvironment of the dye molecules, they interpret the results as indicating changes in the physicochemical properties of the microenvironment of the dye molecules bound to the nerve membrane. They suggest that the observed change in fluorescence when the nerve is active indicates that the macromolecules of the nerve membrane undergo drastic conformational changes that are associated with neural function.

In Cohen, Keyes, and Hille's study, light scattering and birefringence changes were observed during nerve activity. They report rapid structural changes accompanying the action potential in two types of non-myelinated nerve fibers. They suggest that the birefringence phenomena may show that varying electrical fields also have significant effect on the nerve membrane.

To sum then, we have complementary and overlapping hypothesis, Wei's primarily on information transfer, Batteau's primarily on information coding, and Augenstein's primarily on information storage.

There are several other phenomena and possible hypotheses which warrant mention. One is concerned with field induced forces on the neural junction and its effects. A second is the observation that neural tissue can apparently act as a wax electret. The third is the possibility of what can be called microthermal effects. Wiener and Wolman (1967) applied what they report to be a weak electrical field to myelinated nerve and observed shifts in the material in the myelin sheath. They suggest that induced electrical fields may be implicated in certain structural changes in cells such as the formation of synaptic discs. Katz and Miledi (1966) report observing a striking change in neural hormone release when a voltage pulse is applied locally to a motor nerve ending after the action potential wave has already reached its peak at that point. They found that an electrical pulse applied to the extracellular fluid at the nerve terminal during the falling phase of the action potential suppresses the release of the neural hormone. They found that there is a critical period about two milliseconds after the measured peak of the action potential during which the extracellular electrical pulse had an inhibitory effect on the release of the hormone acetylcholine. If the extracellular electrical pulse was applied at any other time, it had no effect on the release of the hormone. Inasmuch as one concept of neural transmission of information involves the release of acetylcholine at the synaptic junction, and acetylcholine is released as quantal packets at the nerve endings i.e. discharges of vesicles containing acetylcholine, an extracellular electrical field pulse effect on this has interesting implications. Inasmuch as the effect is critically dependent upon the time at which the electrical pulse occurs, it would seem worthwhile to experimentally explore this phenomena with rf energy providing the extracellular field effect.

The report of Elul (1966) would lend additional weight to the suggestion that this is a possibility worthy of exploration with rf energy. He observed a displacement of nerve cells in an electrical field in tissue culture experiments. He correctly relates this to the extensively studied electrophoretic migration of cells in uniform electrical fields such as Heller and Schwan have investigated. But, he sees another possible effect and has reported upon it in this paper. He points out that besides the displacement of the entire cell, one must also consider the displacement of a small segment of the cell membrane of a cell that is not free to migrate in the field. He shows that under these conditions, the electrokinetic force can produce a local deformation of the cell membrane. He suggests the possibility of electrokinetic effects at the synapses influencing information transfer in the nervous system. He points out that within the context of chemical theorizing on transmission of information in the nervous system, an almost unmeasurable deformation of the membrane at the synapse could have a rather large effect on information transfer in the nervous system.

Considering now the possibility of neural analogs of wax electrets, the observations of Berg and Naftalin will be briefly mentioned. Berg (1968) has written an interesting paper in which he points out that biological membranes are commonly assumed to be simple dielectrics. He points out that this is not true if molecules with permanent electrical dipole moments are embedded in the membrane. He then develops, through a mathematical argument, that the membrane can behave like wax electret. On the basis of this, he points out that the early receptor potential of the eye, for example, can be related to potentials generated by certain electrets.



Mafatlin (1967) has also considered the electret properties of biological material. He suggests that the hair cells of the organ of Corti in the inner ear may conceivably be constituted in an electret fashion. He bases this suggestion on his experimentation with protein filled models which he used in studying acoustic transduction.

There have also been several suggestions that there can be what are called microthermal effects. Some of the writer's calculations indicate that this is a real possibility. Vogelhut (1968) for example, suggested that rf energy can produce very localized temperature gradients that cause thermoosmotic and thermoelectric aftereffects. His model is based upon the frequency related variation of the dielectric constant of bound and free water and the thermal characteristics of the cellular and interstitial system. Related to this are the essentially "microthermal" concepts of Osipov (1965), who suggested essentially the same thing.

#### Implications.

As may be seen in the foregoing, if we recognize that our knowledge of how the nervous system codes, transfers, and stores information is almost nil, one can list a number of possible mechanisms through which rf energy could affect higher organisms. The problem is not 'is there a possible mechanism' but rather 'which of numerous possible mechanisms' to use as a guide for experimentation. It is only through experimentation that we will obtain the answers about rf effects since calculations flounder on the assumptions that have to be made about how nerves work.

It should be noted that the foregoing is not an exhaustive list of possible mechanisms. It should also be noted that more than one mechanism can be involved in rf effects.

What now can we say about possible hazards of rf energy? Looking back we can see that it is possible with high power density i.e. <sup>somewhat</sup> over 20 mw/cm<sup>2</sup>, to cause cataracts, burn tissue, cause heat prostration, etc. Looking back we also see a large void in experimental data generated in this country. The void is in data relevant to the nervous system and low power density effects at frequencies that penetrate the skin. The writer has seen in his own data effects of low power density energy. But the observation of effects does not necessarily mean the finding of a hazard. Thus, we are left, due to the lack of data, with a large question mark.

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## Figure Captions

Fig. 1. Power distribution in a forehead model neglecting resonance effects and considering only first reflections.

Fig. 2. Computer printout of averaged brain stem evoked response data. Electrode tip placements were in the area of the nucleus subthalamicus, 1, 2; formatio reticularis, 3, 4; nucleus olivaris inferior, 5-8; and nucleus reticularis paramedianus, 9-12. Traces 1, 3, 5, and 9 were obtained during illumination with pulsed rf energy a few minutes before death, and 2, 4, 6, and 10 a few minutes after death. The gap in the rf traces at 1 msec indicates the occurrence of the rf pulses. The acoustic stimuli occurrence have been deliberately omitted and those traces not aligned with the rf since such alignment is not meaningful and might be misleading. The decrease in electronic noise on the averaged traces from the live cats reflects the decrease in amplifier gain necessary to print out their data without the pen going off the paper. Time calibration: 1 msec. Rf illumination was within an echosorb enclosure.

Fig. 3. Computer printout of averaged brain stem evoked response data. Electrode tip placements were in the area of the nucleus subthalamicus, 1-4, and formatio reticularis, 5-8. The PRF for traces 1-4 was 12, 24, 80, 130 pulses/sec and for traces 5-8 was 12, 24, 36, 130 pulses/sec, respectively. The characteristic long latency diffuse activity of the formatio reticularis should be noted



as well as a suggestion of reticular harmonic activity which appeared more clearly in other records not shown. Time calibration: 1 msec. Rf illumination was within an echosorb enclosure.

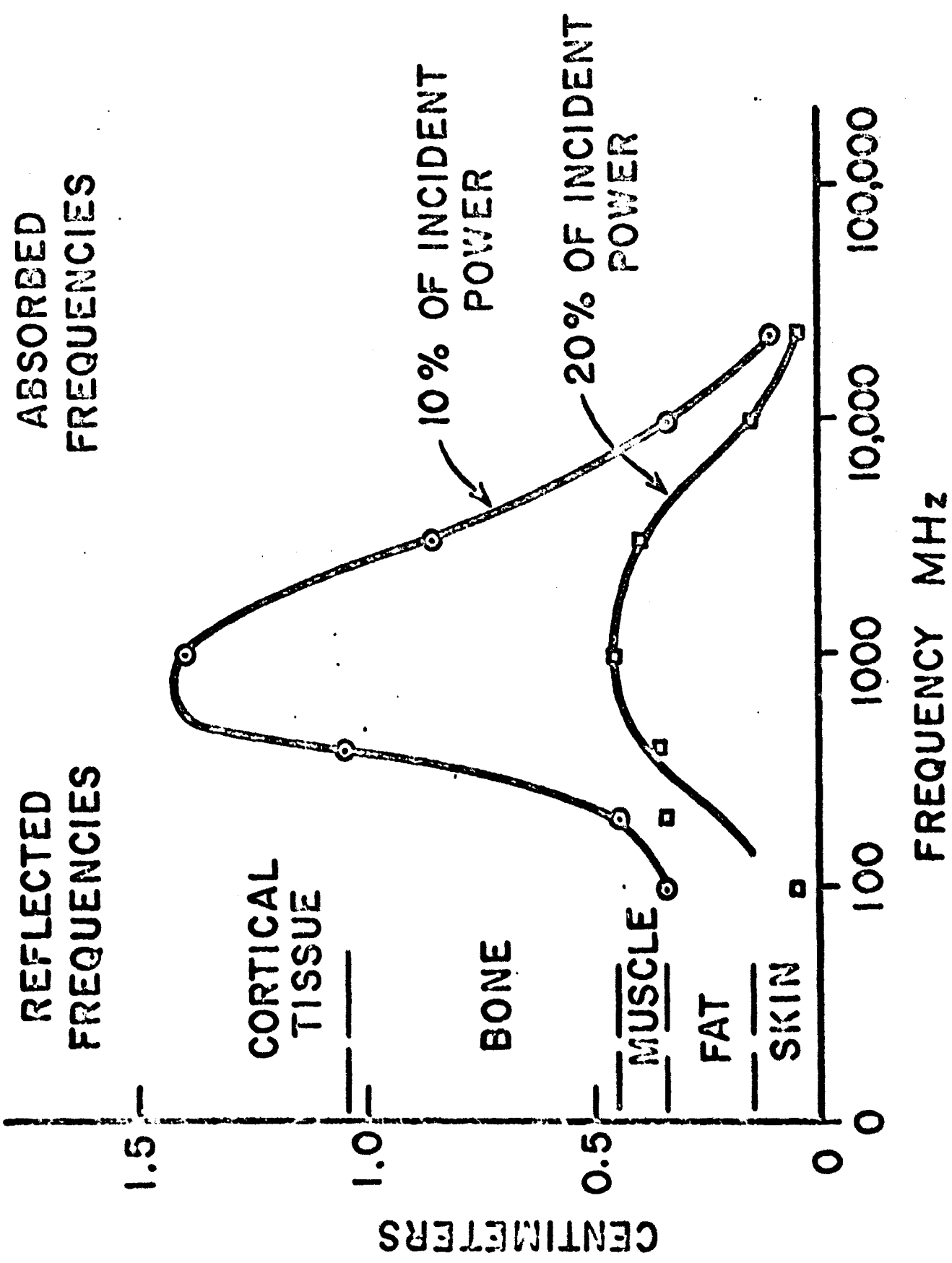
Fig. 4. Threshold energy for the rf hearing effect as a function of frequency of rf energy.

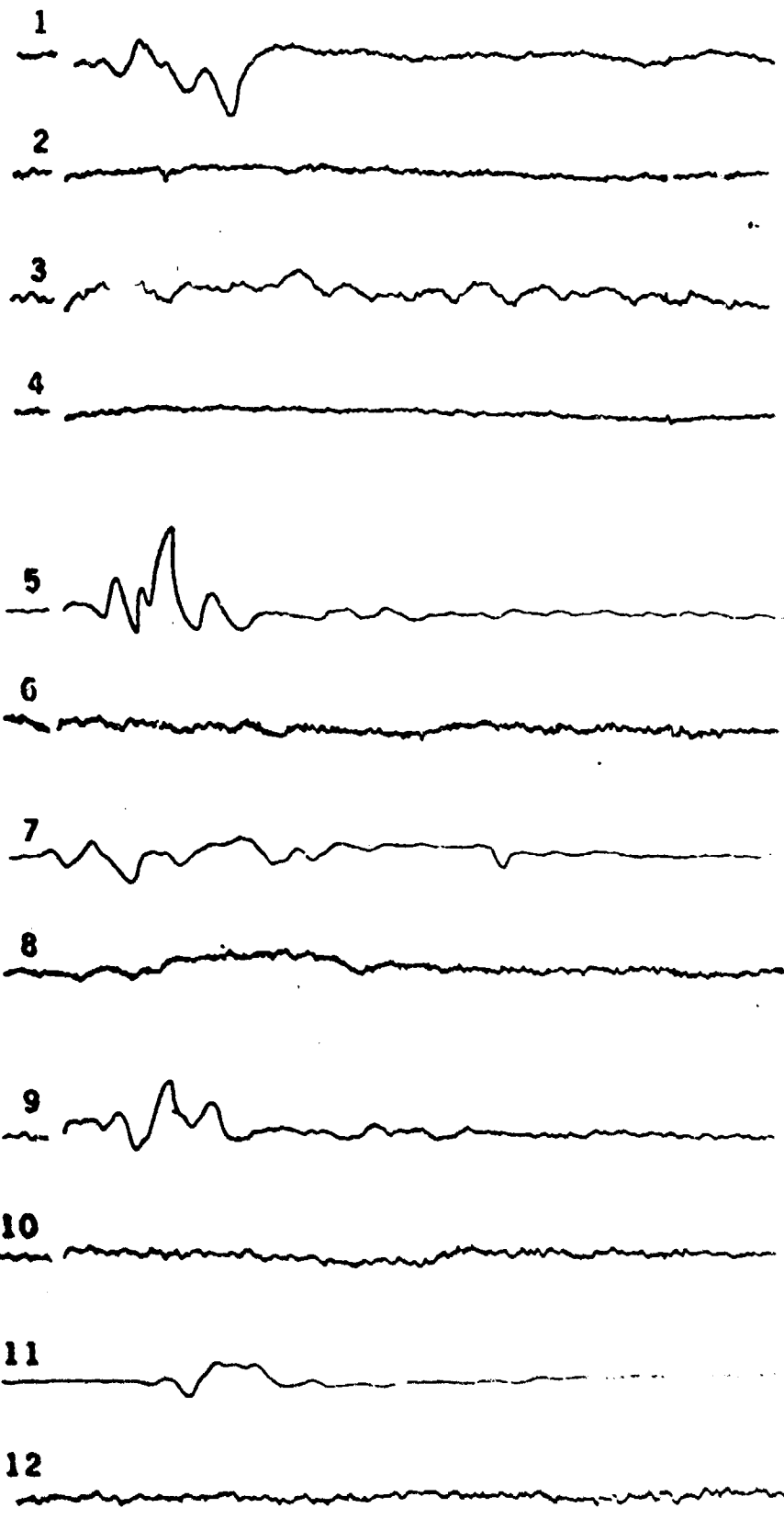
Fig. 5. Calculated point at which energy levels become equal (crossing point) for rf threshold levels in air at two different carrier frequencies.

## FOOTNOTES

1. The Tri-Service Program was the major program in this country concerned with obtaining data on the biological effects of rf energy.
2. J. Fleming, personal communication, 1962.

Much of the writer's experimentation discussed herein was supported by contracts with the Office of Naval Research.





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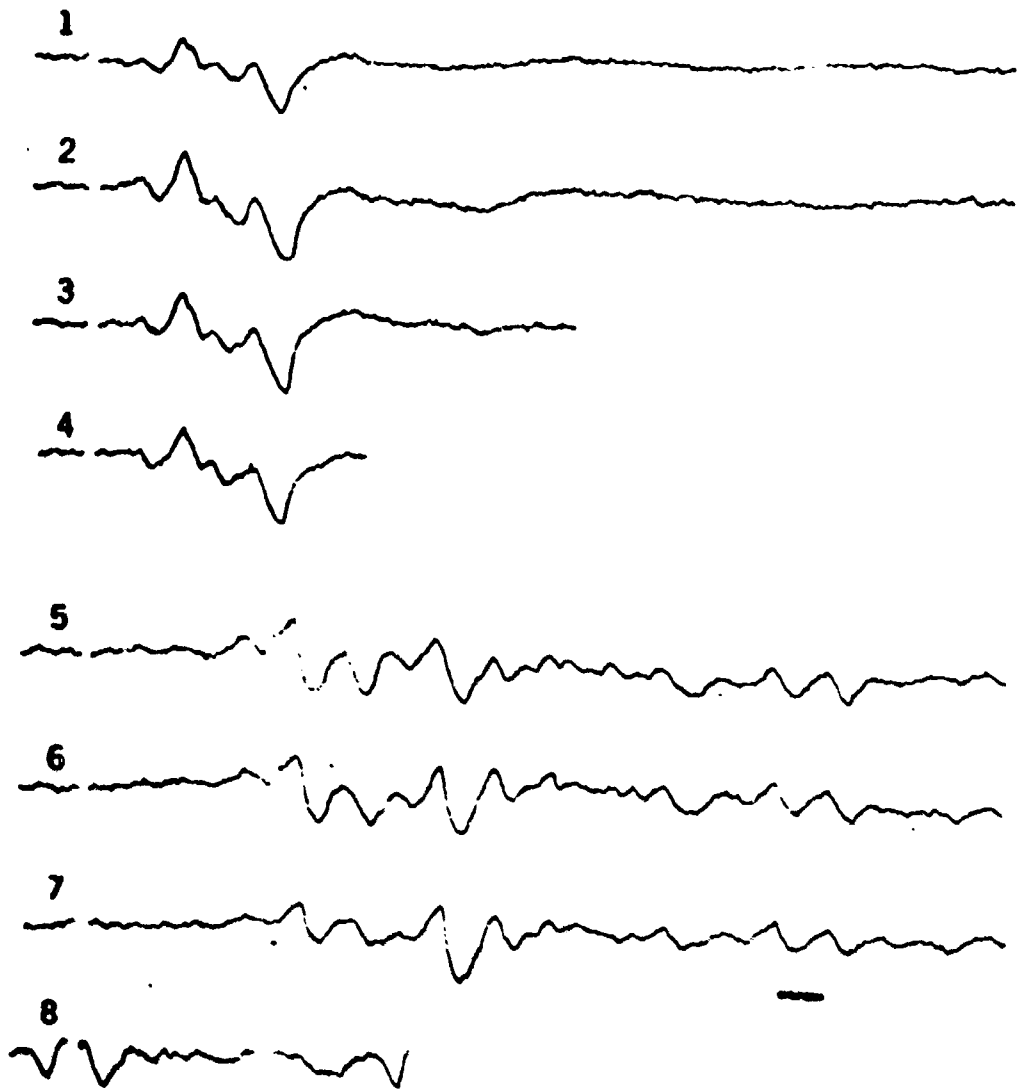
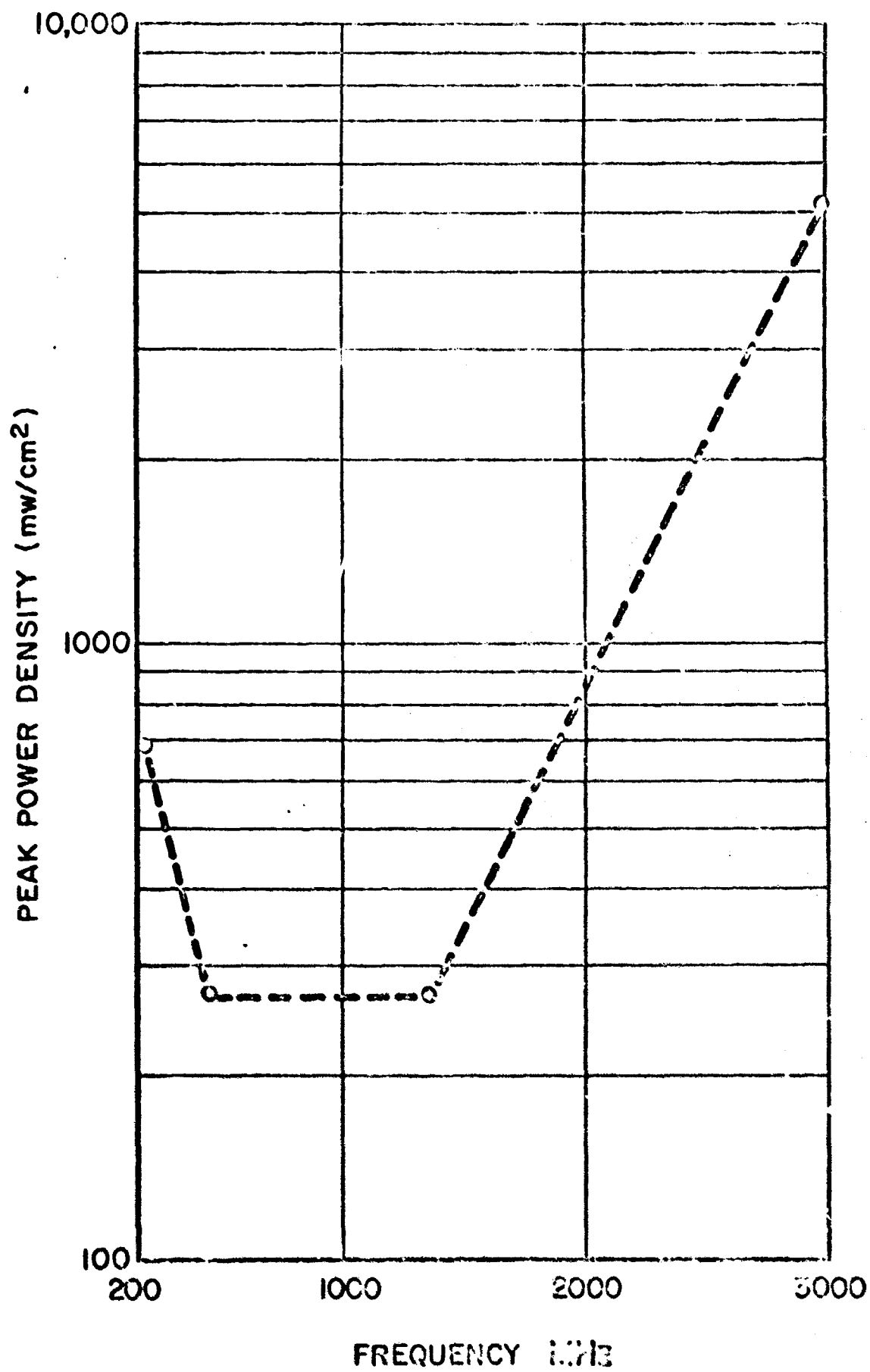


Figure 1





UHF Signal Penetration

3 GHz

1.3 GHz

Power density increasing →

NOT REPRODUCIBLE

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5 AUTHOR(S) (Last name, first name, initial)			
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<p>In recent years, it has been recognized that low power density modulated rf energy can affect the functioning of higher living organisms. In this paper the sparse data generated in the western hemisphere on this subject is considered, the reasons for its sparseness noted, and the hypotheses on mechanisms that may provide an explanation for the observed effects and other possible effects are sketched. Possible conclusions with regard to hazards to personnel are then considered.</p>			



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